Optimum Well Spacing for Geothermal Power

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ABSTRACT

The closer the distance between production wells, the lower the field development cost, due largely to the high price of steam transmission lines. For underground systems where flow is through fissured formations, it is found that wells of fairly large discharge can be quite close together (order of 50 m) without interaction effects. Calculations indicate that this applies both to hot-water fields and to those tapping dry-steam reservoirs. Hence well spacing for a hot-water system should still be appropriate if discharges are changed to dry steam.

INTRODUCTION

Exploitation of a geothermal reservoir by drill holes can cause two effects. The first is that the discharge can lead to a steady reduction in the underground pressure, leading to a decline in well output and a shortening of the economic life of the project. The second effect is due to the wells being located too close to one another with reduced output due to the discharge of neighboring wells. These two effects do not seem to be related, and neither has been satisfactorily estimated beforehand for any of the geothermal fields at present being exploited.

The pragmatic approach adopted is to expand the development of a field in stages, with a wary eye kept on the decline in reservoir pressure. This is plotted to a time base, and extrapolations are made, backed up by some theory (usually not very reliable) in order to estimate future values. To avoid possible interaction between discharging wells, well spacing is usually kept rather large, at least initially; and it is only when the field has been extensively developed that reality has indicated what might be called the best spacing for that particular region. Of course, because of the nonuniformity of the underground systems, it is impossible to impose a specific well-spacing grid on a given field; hence there is a certain amount of variability in the results for places such as Wairakei and The Geysers, for example.

At Wairakei, more than half of the 60 production wells are spaced between 50 and 70 m apart for steam-water discharges originally averaging about 600 000 lb/hr (272 tonne/hr) for holes of 8 in. diameter (20 cm) drilled into a hot-water reservoir of 250°C temperature.

For 8-1/2-in. diameter (21.6 cm) holes at The Geysers which produced originally up to 150 000 lb/hr of dry steam (68 tonne/hr), an average spacing as low as 90 m has been used (Budd, 1973) in certain areas. This is, of course, for a steam system with a reservoir pressure up to 500 psia (34.5 bar).

In Iceland, a spacing of 85 to 90 m is employed for wells of 6 to 7 in. diameter (15.2 to 17.8 cm) which discharge steam-water mixtures for the power plant of Bjarnarflag, according to Ragnars et al. (1970). The separated steam is about 25 tonnes/hr at 11-bar pressure.

Dry steam wells of 12-in. diameter (30.5 cm) at Travale, Italy, are spaced from 100 to 180 m (Cataldi et al., 1970), while the steam-water wells of Otake, Japan, are from 80 m apart for 6-in. diameter holes (15.2 cm; Hayashida and Ezima, 1970).

The exploration program often dictates the well spacing, hence the spacing distance from about 150 m for the hot-water reservoirs of Kızıldere, Turkey (205°C), and of El Tatio, Chile (261°C). No interaction was found between wells in both these fields, even when the holes were discharged wide open vertically with individual wells flowing up to 500 tonnes/hr in Kızıldere and 270 tonnes/hr in El Tatio. When wells are on production, their flows are much less than the maximum vertical (often of the order of 70%); hence in this case there is even less chance of interaction effects.

It appears that reasonably large flows from geothermal wells are derived from underground flow through cracks in fairly impermeable rock, although there are, of course, exceptions to this (James, 1975). We shall therefore mainly consider in this paper the case of a horizontal crack or fissure through which the hot fluid flows radially into a borehole. For a crack of uniform width at some distance from the well, the fluid moves very slowly, gathering speed as it approaches the uncased hole until its velocity reaches a maximum at the rim of the hole. The reservoir pressure is hardly affected at some distance from the well; but as the fluid moves towards the hole, its pressure is reduced steadily by frictional resistance of the walls of the crack. As it nears the hole, the kinetic energy increase of the accelerating fluid increases the decline in pressure. For a horizontal crack, there is no change in pressure due to differences in hydrostatic level; and even if we consider a crack oriented at a sharp angle to the horizontal—such as must happen in practice—the fluid rising into the hole is probably compensated by that descending into it, hence the horizontal case probably does not introduce significant error.

CALCULATIONS OF HORIZONTAL FLOW

Pressure Drop Due to Resistance

Over an increment of radius (Fig. 1 and Table 1), the pressure and shear stress forces are:

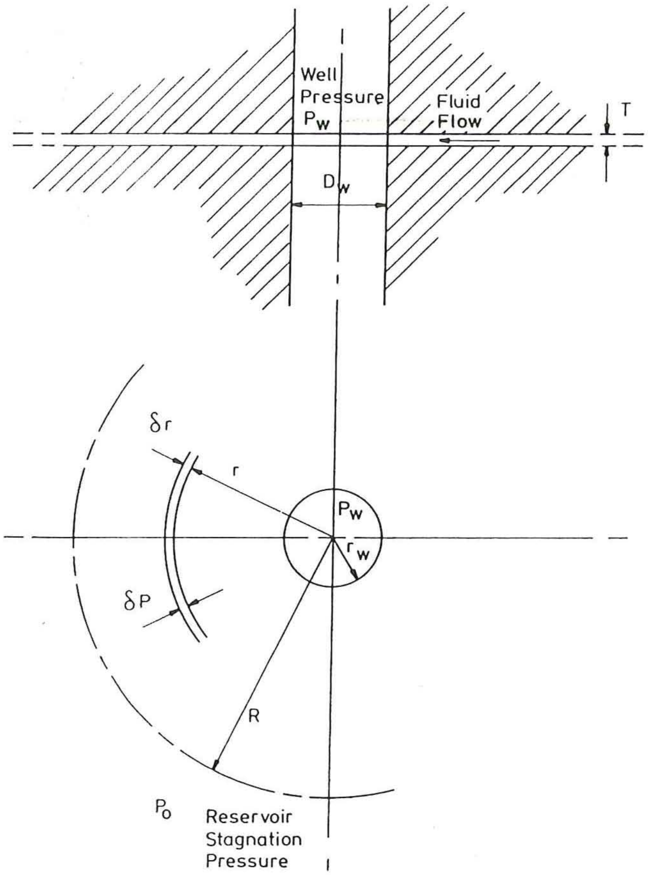

Figure 1. Horizontal crack in impermeable rock penetrated by borehole.

Table 1. Notation.

D_w	=	well diameter at crack, ft
d_w	=	well diameter at crack, inches
f	=	fanning friction factor
G	=	mass-velocity, lb/(ft)^2 sec
g	=	gravitational constant, ft/(sec)^2
P_o	=	static reservoir pressure, lb/(ft)^2 abs
P_w	=	pressure in well at depth of crack, lb/(ft)^2 abs
ΔP_f	=	fractional drawdown pressure differential, lb/(in)^2
ΔP_k	=	pressure drawdown due to kinetic energy, lb/(in)^2
δP	=	differential pressure increment, lb/(ft)^2
q	=	flow, ft^3/sec
Re	=	Reynold's number
R	=	radius to where reservoir pressure unvarying, ft
r_w	=	borehole radius at crack depth, ft
r	=	any radius, ft
δr	=	differential radius increment, ft
T	=	crack width, ft
t	=	crack width, inches
u	=	fluid velocity, ft/sec
V	=	specific volume, ft^3/lb
W_k	=	fluid flow rate, thousand pound/hr
μ	=	fluid viscosity, centipoise
τ_0	=	fluid shear stress, lb/(ft)^2 abs

$$\delta P\, 2\pi r\, T = \tau_0\, \delta r (2\pi r)\, 2$$

where the shear stress $\tau_0 = \dfrac{fu^2}{2gV}$

hence $\delta P = \dfrac{2\, fu^2\, \delta r}{TV2g}$

and $u = \dfrac{q}{2\pi r T}$

$$\delta P = \frac{2fq^2}{2g4\pi^2 T^3 V}\left(\frac{\delta r}{r^2}\right) \qquad (1)$$

For typical borehole flows, the flow regime is turbulent over most of the path where pressure drop takes place; hence $R_e > 2000$ and $f = \dfrac{0.0344}{R_e^{0.1505}}$ (from Perry, 1963)

and $R_e = 1488 \dfrac{GT}{\mu} = \dfrac{1488\, q}{2\pi r \mu V}$

where $G = \dfrac{q}{2\pi r T V}$

Substituting for f and R_e in (1), we have:

$$\int_{P_w}^{P_o} \delta P = \frac{2\,(0.0344)}{2g4\pi^2 \left(\dfrac{1488}{2\pi}\right)^{0.15}} \frac{q^{1.85}\mu^{0.15}}{T^3 V^{0.85}} \int_{r_w}^{R} \left(\frac{\delta r}{r^{1.85}}\right)$$

$$P_o - P_w = 1.19\,(10)^{-5} \frac{q^{1.85}\mu^{0.15}}{T^3 V^{0.85}} \left[\frac{1}{0.85\, r_w^{0.85}} - \frac{1}{0.85\, R^{0.85}}\right]$$

The term involving R within the brackets has a negligible effect and so is eliminated, and substituting $D_w/2$ for r_w and $W_k\, V/3.6$ for q,

$$P_o - P_w = 2.35\,(10)^{-6} \frac{W_k^{1.85} V \mu^{0.15}}{T^3 D_w^{0.85}}$$

Substituting drawdown ΔP_f psi for $\dfrac{P_o - P_w}{144}$,

$$\Delta P_f = 1.63\,(10)^{-8} \frac{W_k^{1.85} V \mu^{0.15}}{T^3 D_w^{0.85}}$$

Substituting t inches for 12 T, and d_w inches for 12 D_w, we have:

$$\Delta P_f = 2.32\,(10)^{-4} \frac{W_k^{1.85}\, V \mu^{0.15}}{t^3 d_w^{0.85}} \qquad (2)$$

where ΔP_f = frictional pressure drawdown in psi, W_k is flow in thousands of pounds/hr, V is specific volume of fluid in ft^3/lb; μ is viscosity in centipoise, t is crack width in inches, d_w is well diameter in inches.

Pressure Drop Due to Kinetic Energy

As the fluid passes from the periphery at a pressure P_o to the well rim at a pressure P_w, the kinetic energy increases as follows:

$$P_o - P_w = \frac{u_w - u_o}{2gV}$$

The pressure drop $\Delta P = \dfrac{P_o - P_w}{144} = \dfrac{u_w - u_o}{2\, g\, V\, 144}$ psi substituting $u = \frac{W_k V}{(3.6)\, 2\pi r T}$ for constant V

$$\Delta P = \left(\frac{W_k}{7.2\,\pi T}\right)^2 \frac{V^2}{2\,g\,V\,144}\left[\left(\frac{1}{r_w}\right)^2 - \left(\frac{1}{R}\right)^2\right]$$

$$\Delta P = \left(\frac{W_k}{T r_w}\right)^2 \frac{V}{4.74\,(10)^6}$$

where $\left(\frac{1}{R}\right)^2$ is negligible.

Substituting t inches $= 12\ T$; and d_w inches $= 24 r_w$

$$\Delta P_k = \left(\frac{W_k}{7.5\, d_w t}\right)^2 V \qquad (3)$$

where ΔP_k is pressure drop in psi due to kinetic energy increase in fluid flowing, W_k is flow in thousands of pounds/hr, d_w is well diameter in inches, t is crack width in inches, and V is specific volume of flowing fluid in ft^3/lb.

OVERALL PRESSURE DROP

The total pressure drop ΔP_t within the crack from the reservoir stagnation pressure to the value just at the rim of the well is the sum of equations (2) and (3), namely:

$$\Delta P_t = \Delta P_f + \Delta P_k$$

However, for geothermal boreholes with reasonably good flows, the bottom-hole pressures remain fairly high and the high speed of the fluid in the rim of the crack slows down to match the relatively low velocity flowing vertically at the hole bottom. Hence the kinetic energy is nearly all converted to pressure within the hole; and because of this, the measured pressure drawdown in the hole $\Delta p \simeq \Delta p_f$.

As suggested by James (1975), it is not likely that flashing takes place within the crack, even though the pressure of the flowing fluid can be reduced below the saturated vapor pressure associated with the water temperature. This is because this condition occurs very close to the well and the velocity is high; hence little time is available for bubble nucleation.

WELL SPACING

If the pressure drawdown in a well is given by formula (2), the fall in pressure from the periphery to a value, say, of 1% of ΔP_f will take place at a certain radius from the well. If we let d_s be the diameter associated with this radius, then:

$$0.01\,\Delta P_f = 2.32(10)^{-4}\frac{W_k^{1.85}\, V\, \mu^{0.15}}{t^3\, d_s^{0.85}} \qquad (4)$$

Dividing formula (2) by (4), we have

$$\frac{d_s}{d_w} = (100)^{1/0.85} = 225 \qquad (5)$$

This formula is nondimensional and indicates that a reasonable well spacing would be equivalent to $d_s = 225\ d_w$. For example, at Wairakei, the well spacing for 8-in. boreholes (0.02 m) would be $225^{0.02}$ m = 45 m which is in accord with the actual range of 50 to 70 m for most of the production wells, as interaction has not been noted in practice.

The effect of two wells drilled at a spacing found according to formula (5) would be that at a point intermediate between them, there would be a fall in the reservoir pressure of 2% (each well contributing 7%). As the flow through a horizontal crack would be from a full circumference, the effect of such a slight pressure depression on one small sector should have no significance to the flow. Of course, if a hexagonal grid pattern of wells were drilled into such a horizontal crack, it would be best to increase the well spacing by, say, 100% to avoid interaction; but most fields have boreholes spaced along a fault line or some other geological feature at which the spacing advocated above could be used.

For the case of a reasonably good dry-steam borehole with a fairly high bottom-hole pressure when on production, the average specific volume of the steam passing along the crack is not likely to increase by more than about 1.5 times its value at the stagnation reservoir pressure. This results in an approximately 1.5% fall in pressure compared with the 1% of the hot water case above. Hence there is little difference discernable between the two types of fluids, and formula (5) is applicable to both. So a well-spacing configuration which is working satisfactorily on a hot-water system should give equally good results if the reservoir alters to a dry-steam one. If the steam reservoir pressure becomes low (less than, say, 200 psig), the well discharges will also be low, but this would be true whatever the well spacing and is roughly independent of formula (5).

If well discharges are poor, well spacing will be large in order to locate zones of higher permeability which, if discovered, permit the closer arrangement described above.

CONCLUSIONS

It appears that well spacing can be somewhat less than is found in most successful geothermal fields. It is understandable that such distances are excessive, as boreholes are expensive and field engineers wish to avoid the possibility of pressure interaction leading to reduction in discharges.

The selection of drilling sites is a very difficult undertaking, and it is not suggested that the spacing formula (5), derived here, be imposed on a developing field; rather it is offered as a guide to just how close one can drill in the areas where crack permeability is good.

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